Part I

Theoretical Aspects

1

Introduction to WLL: Digital Service Technologies

Ioannis S. Barbounakis and Peter Stavroulakis

1.1 Background

During the last few years, the telecommunications sector has progressed remarkably thanks to the numerous technological advances occurring in the field. The demand for communication services has also increased explosively worldwide creating or imposing tougher capacity requirements on the telecommunication infrastructure. In developing regions, this demand reflects the great need for the basic telephone services, i.e. the *Plain Old Telephone Service* (POTS), whereas in developed regions it applies to high-rate data and multimedia services at home and/or office. In addition to these recently established conditions, the liberalization of the telecommunication sector, taking place in our days, has unexceptionably driven innovation on the telecommunication infrastructure. It is only the local loop segment that has left unchanged despite all these technological innovations. Lately, however, it has attracted the attention of telecommunication carriers since it proves to be the bottleneck in their network expansion. Consequently, more efficient transmission techniques (ISDN, DSL) improving the capacity of the copper wires or alternative physical media such as fibre, coaxial cable and wireless terrestrial or satellite links have started to be deployed more and more.

It is not only the rapid penetration, which is necessary in developing regions, but also the need for higher capacity in developed regions that have made other physical media apart from our common copper wiring viable solutions in the local loop arena. Today's copper wiring is mostly limited to a maximum distance of 5 km between the subscriber and the local exchange, with the average being in the region of 2 km. This class of transmission channels is sufficient in providing POTS and data through voice-band modems. Moreover, it has reached its upper limits and only thanks to digital techniques such as *Integrated Services Digital Network* (ISDN) and *Digital Subscriber Line* (DSL), it keeps a high competitiveness. ISDN has been the first digital transmission technology to work over existing copper lines offering voice, data and low-resolution video simultaneously. DSL technology has followed offering data and voice integration with a higher efficiency than ISDN but at the cost of farther limitations. DSL lines must be clean copper from the local exchange to the customer premises. The service also degrades dramatically as the distance from the local exchange increases, limiting bandwidth available to customers or preventing access to more rural users. Asymmetric DSL is the technology favoured by many operators or Internet Service and Multimedia Content Providers. Downstream speeds typically are much faster than the upstream speeds. Symmetric DSL is more popular with *local exchange carrier*s (LECs), which locally compete with incumbent operators for customers. Connection speeds are the same in both directions.

Optical fibre has been utilized in the trunk network as a more efficient and cost-effective solution for many years now. In many countries it has also replaced copper in the distribution network. However, when considering the local loop the undertaking becomes too risky mainly due to the high cost involved in such a large-scale deployment.

Cable television has become a reality to many people worldwide for more than 20 years now. When the customer base grew up to a significant level, cable operators thought of providing telephony services through a new type of bidirectional cable modem. Although the coaxial cable is a high-bandwidth channel, the fact that only selected areas of the world and selected populations within these areas would be interested in services other than CATV make this medium cost-ineffective for a local loop option.

Another solution, which adopts radio as the transmission medium, in the local loop is the *wireless local loop* (WLL). WLL is often called the *radio local loop* (RLL) or the *fixed wireless access* (FWA). Since WLL is a kind of radio system, it is natural that its technology has been affected by wireless mobile communication technologies. In fact, as will be shown later, most WLL systems have been developed according to the standards (or their variants) for second-generation cellular and cordless systems. However, until now that third-generation cellular systems, i.e. *Universal Mobile Telecommunication Systems* (UMTS) start to be deployed, WLL systems were at a disadvantage compared to their wireline counterparts in terms of voice quality and data rates supported. In general, almost all of cellular/cordless systems or multiple access techniques can be used for narrowband WLL. However, it is also true that there exist some technologies or systems that have comparative advantages in a certain WLL environment.

Many manufacturers and TV broadcasters have been promoting the idea of deploying terrestrial microwave distribution systems mainly for television provision as broadband wireless systems. The philosophy behind such systems is to provide a reverse link as well. Services like Video on Demand and wideband Internet connections are among the first to be offered. At the assigned microwave frequencies, high propagation losses and weather effects such as heavy rain play an important role in the power budget design of the system probably making it a less favoured solution for wireless local loop access in rural and sparsely populated areas.

Last but not least, there are the satellites, which support network access to all subscribers rather than only the fixed ones. Despite the long delays and the high equipment cost, they will play an important role in providing global network access to rural areas not available through other means or small communities with a minimum degree of mobility.

In this chapter, we attempt an overview of several WLL digital service technologies, which have been developed during the last years. We classify them according to their range, capacity and air-interface specifications standardized or not. Through their presentation, our aim is to conclude on what WLL is able to offer to the developing and developed world now and in the foreseeable future.

Section 1.2 outlines the advantages of efficient WLL systems in developing and developed regions. Section 1.3 focuses on the requirements that WLL has to meet in order to compete in the local loop arena. Section 1.4 presents a generic WLL system architecture and focuses on the technological breakthroughs in the wireless transceiver architecture on a per functional block basis. Section 1.5 describes the digital service technologies, which are in the phase of deployment or trial worldwide. Section 1.6 compares all WLL candidate technologies in terms of range, quality, service capability, etc. Finally, concluding remarks are derived in Section 1.7. For completion purposes, two appendices are given. Appendix A clarifies the differences of cellular technologies being deployed with fixed instead of mobile subscribers. Appendix B constitutes an answer to the question 'which multiple access format is more efficient: CDMA or TDMA?'.

1.2 Advantages of Wireless Systems

Wireless systems are justified as a local loop solution because of the cost-effectiveness and/or limitations of other technologies such as copper, coaxial cable and fibre. However, there has not been established any standard for WLL yet. WLL systems, which are currently deployed, are based on a wide range of radio technologies including satellite, cellular/cordless and many proprietary narrowband or broadband technologies depending on the desired subscriber density as well as on the coverage area under service (see Figure 1.1).

WLL has many advantages from the viewpoints of the service providers and subscribers [1–7]:

Fast Deployment WLL systems can be deployed in weeks or months as compared to the months or years needed for the deployment of copper wire systems. Faster deployment can mean sooner realization of revenues and reduced time to payback of the deployment investment. Even with higher costs per subscriber that may be associated with the WLL terminal and base station equipment, the faster rate of deployment can permit a higher return of investment. The rapid rate of deployment can also yield first-mover advantage with respect to competitive services, can accelerate the pace of regional economic growth, and can provide substantive progress in the development of needed infrastructure.

Low Construction Cost The deployment of WLL technology involves considerably less heavy construction than does the laying of copper lines. The lower construction costs may be more than offset by the additional equipment costs associated with WLL technology, but in urban areas, especially, there may be considerable value in avoiding the disruption that the wide-scale deployment of copper lines entails.

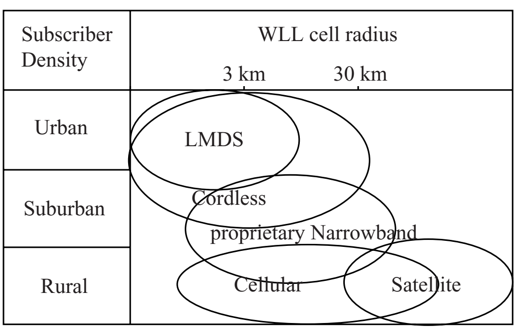

Figure 1.1 WLL coverage using different technologies

Low Operations and Maintenance Cost The operations and maintenance are easy and the average maintenance time per subscriber per year is shorter 3 to 4 times than their wireline competitors.

Customer Connection Cost It is low, so overall 'cost per customer' is significantly lower than wireline or cellular systems.

Lower Network Extension costs Once the WLL infrastructure—the network of base stations and the interface to the telephone network—is in place, each incremental subscriber can be installed at very little cost. WLL systems that are designed to be modular and scaleable can furthermore allow the pace of network deployment to closely match demand, minimizing the costs associated with the underutilized plant. Such systems are flexible enough to meet uncertain levels of penetration and rates of growth.

High Handwidth Services Provision Using advanced digital radio technologies, WLL can provide a variety of data services and multimedia services as well as voice.

High System Capacity Among radio systems, WLL enjoys the merits of fixed system: using high-gain directional antennas, the interference decreases. This reduces the frequency re-use distance, increases the possible number of sectors in a sectored cell, and increases, in turn, the system capacity (see Appendix A).

1.3 WLL Service Requirements

The services offered depend strongly on the customer segment. These will in turn impact the bandwidth required to deliver the service and hence the supporting technology, since not all can deliver the high rates required for advanced services.

The emergence of ADSL, cable network upgrades for data services and developments in 3rd-Generation mobile all impact the WLL service in a competitive environment. They drive the minimum data rate needed for a fixed wireless solution to remain competitive in the residential segment. With the introduction of broadband wireless technologies, data rates of more than l0 Mbit/s are now possible, accommodating bandwidth intensive applications such as video-on-demand or LAN interconnect. The broadband wireless systems being deployed worldwide today are targeting mainly multitenant business buildings with E1/T1 services for aggregated telephony or IP traffic.

A summary of service needs for different customer types is shown in Table 1.1. In all cases, if WLL systems have to be competitive in service provision to alternative suppliers, they have to satisfy the following requirements that vary with respect to the servicing area, the target group of potential customers and the kind of services offered:

Communications Quality Since a WLL system serves as an access line for fixed telephone sets, it must provide the same level of quality as conventional telephone systems with respect to such aspects as speech quality, *grade of service* (GOS), connection delay and speech delay.

Table 1.1 Service needs per customer type

Customer\Service	Basic Telephony	Internet data/fax	BRA ISDN	$n \times 64/56$ Kbps	$n\times$ E1/T1 PRA ISDN	LAN ATM	MPEG2	IN functions
Very large business	■	■	■	■	■	■		■
Large business	■	■	■	■	■	■		■
Medium business	■	■	■	■	▼	▼		■
Small Business	■	■	■	■				■
SOHO	■	■	■	■				▼
High spending resident	■	■	■	▼			■	
Med spending resident	■	■	■				▼	
Low spending resident	■	▼						

■ : means full use ▼ : means partial use

Secure Transmission WLL must be secure to give the customer confidence that conversation remains confidential. The system should also include authentication to prevent fraudulent use.

ISDN Support The system should support integrated services digital network (ISDN) when appropriate to provide voice and data service.

Easy Environment Adaptation The system should be capable of small-cell or large-cell operation to serve dense urban or rural areas respectively.

Absence of Interference with Other Wireless Systems A WLL system must not cause any interference with the operation of existing systems, such as microwave communications and broadcasting systems.

High Traffic Volume One characteristic of a WLL system is that it must support a larger traffic volume per subscriber than mobile or even wireline communications systems.

High Capacity and Large Coverage The maximum system range and base station capacity should be large to make the 'cost per subscriber' as low as possible and minimize the entry cost for an operator.

A first assessment of these requirements shows that from the subscriber's perspective service quality and confidentiality as well as bandwidth availability are of great importance. From the perspective of the system operators, the high priority requirements of WLL systems are high-capacity and large coverage. Technically, it is a big challenge to meet these two contradicting sets of requirements and still lower the cost of deploying a WLL system and utilize the spectrum efficiently. Since the three key drivers—voice quality, coverage, and capacity—are always competing among themselves, one may have to determine an acceptable voice quality level first, and then choose a WLL technology that can provide high-capacity and large coverage.

1.3.1 Developing Regions

In many developing regions, the infrastructures for basic telephone services are still insufficient. Accordingly, a lot of population in these areas has not been served with even plain telephony service. For these areas, the requirements of WLL services can be summarized in the following:

- In terms of service coverage, a wide area should be covered within relatively short period.
- Especially, for the regions with dense population, a high-capacity system is indispensable. Here, the capacity is the available number of voice channels for a given bandwidth.
- On the other hand, there may exist wide areas with sparse population. For these service areas, if a small population with low traffic load resides near by, a centralized FSU serving more than one subscriber can be a solution.
- The service fee per subscriber must be low so as to offer the universal service. For this, a high-capacity system is again needed and the cost of system implementation and operation should be low.
- The system should be implemented rapidly so that the services might be launched quickly.

As a trade-off to fulfil the requirements of high-capacity with low service fee, a medium-quality and relatively low data rate of channel (typically, up to 16 kbps) may be unavoidable. Using this channel, only voice and/or voice-band low-rate data communications are possible. However, at the initial choice and installation of WLL system, the service provider should take into account the future evolution of system to provide advanced services.

1.3.2 Developed Regions

In the developed regions, the service requirements contain not only POTS but also other advanced services. It is usual that more than one local exchange carriers and cellular mobile service providers coexist in these service areas. We examine the WLL service requirements from the standpoint of each service provider.

WLL provides a means to establish local loop systems, without laying cables under the ground crowded with streets and buildings. Thus, WLL is regarded as one of the most attractive approaches to the second local exchange carriers. Unfortunately from the second providers' perspective, there are one or more existing providers (i.e. the first providers) who have already installed and operated wireline networks. To meet the increasing and expanding users' service requirements for high-rate data and multimedia services as well as voice, the first providers try to evolve their networks continually (for example, using DSL technologies). The second providers, entering the market in this situation, should offer the services containing competitive ones in terms of service quality, data rate of channel, and supplementary services, etc. That is, the WLL channel of the second provider should be superior to or, at least, comparable with the first operators' one in quality and data rate. Therefore, WLL should provide toll quality voice and at least medium-rate data corresponding to the integrated services digital network (ISDN) basic rate interface (BRI, 2B + D at 144 kbps). In addition, to give subscribers a motivation to migrate to the new provider, the service fee of the second provider needs to be lower than that of the first operators.

Even to the first local switching service providers having wireline networks, WLL can be a useful alternative for their network expansion. Most countries impose the *universal service obligation* (USO) upon the first operators. In this case, WLL can be considered as a supplementary means to wireline networks, for covering areas with sparse population, e.g. islands. The first service requirement for this application of WLL is the compatibility with and the transparency to the existing wireline network. On the other hand, the cellular mobile service providers can offer easily WLL services by using their existing infrastructure for mobile services. In this case, *fixed* WLL service may have competitiveness by combining with the *mobile* services. For example, these two services can be offered as a bundled service [5,8–9]. That is, with a single subscriber unit, a subscriber enjoys the fixed WLL services at home and the mobile services on the street.

1.4 Generic WLL System Architecture

Since WLL systems are fixed, the requirement for interoperability of a subscriber unit with different base stations is less stringent than that for mobile services. As a result, a variety of standards and commercial systems could be deployed. Each standard (or commercial system) has its own air-interface specification, system architecture, network elements, and terminology. Moreover, under the same terminology, the functions of the elements may differ from system to system. In this section, we present a generic WLL architecture (see Figure 1.2).

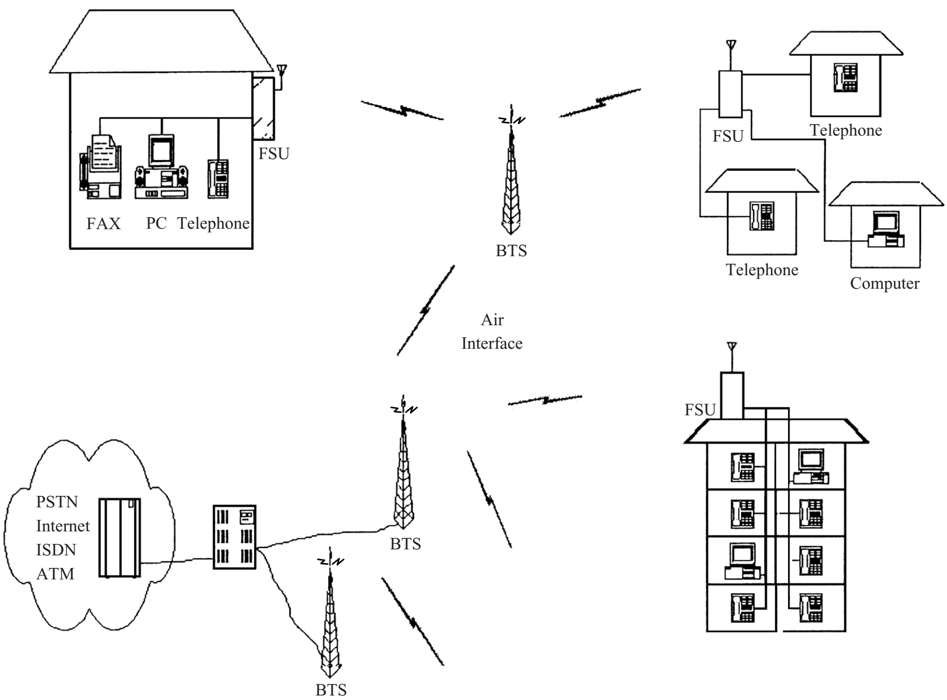

Figure 1.2 Generic WLL architecture

The *fixed subscriber unit* (FSU) is an interface between subscriber's wired devices and WLL network. The wired devices can be computers or facsimiles as well as telephones. Several systems use other acronyms for FSU such as the *radio subscriber unit* (RSU), or the *fixed wireless network interface unit* (FWNIU). FSU performs channel coding/decoding, modulation/demodulation, and transmission/reception of signal via radio, according to the air-interface specification. If necessary, FSU also performs the source coding/decoding. FSU also supports the computerized devices to be connected to the network by using voice-band modems or dedicated data channels.

There are a variety of FSU implementations. In some types of commercial products, the FSU is integrated with the handset. The basic functions of this integrated FSU are very similar to those of the mobile handset, except that it does not have a rich set of functions for mobility management. Another example of FSU implementation is a high-capacity, centralized FSU serving more than one subscriber. Typical application of this type of FSU can be found in business buildings, apartment blocks, and the service area where some premises are located near by (see Figure 1.3).

FSU is connected with the base station via radio of which band is several hundreds of MHz till up to 40 GHz. Since WLL is a fixed service, high-gain directional antennas can be used between FSU and the base station, being arranged by line-of-sight (at least, nearly). Thus, WLL signal channel is a Gaussian noise channel or strong Rician channel (not a Rayleigh fading channel) [6]. This increases drastically the channel efficiency and the capacity of the system.

The base station is implemented usually by two parts, the *base station transceiver system* (BTS) and the *base station controller* (BSC). In many systems, BTS performs channel coding/decoding and modulation/demodulation as well as transmission/reception of signal via radio. BTS is also referred to as the *radio port* (RP) or the *radio transceiver unit* (RTU).

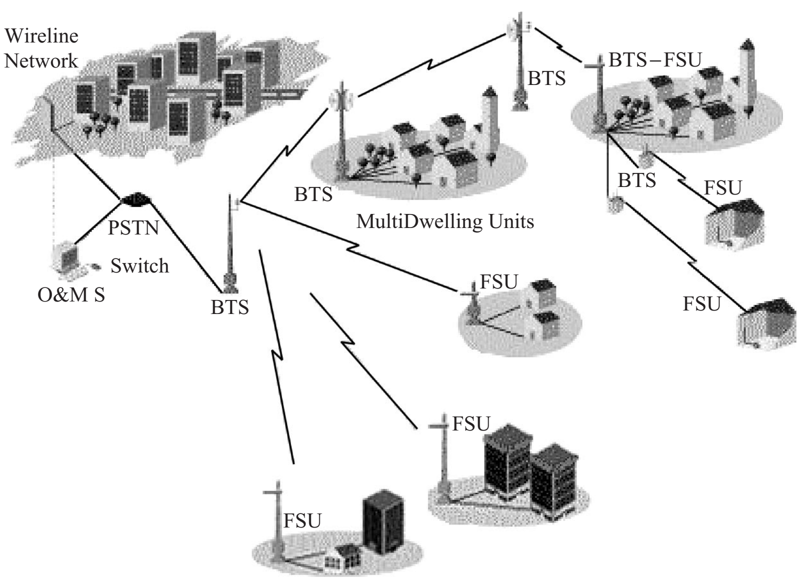

Figure 1.3 FSUs serving multiple subscribers

A BSC controls one or more BTSs and provides an interface to the local exchange (switch) in the central office. An important role of BSC is to transcode between the source codes used in wired network and that at the air-interface. From the above roles, a BSC is often called the *radio port control unit* (RPCU) or the *transcoding and network interface unit* (TNIU).

WLL systems provide fixed wireless access and therefore they do not need to support any mobility features like handover, even though some of these systems are based on cellular standards and products. For a complete comparison between fixed wireless and cellular systems one should refer to Appendix A.

As one can easily understand from Figure 1.2, the WLL services depend not only on the functionality of FSU, BTS, BSC, and air-interface specification but also on the service features provided by the switch in the central office. For example, when WLL is used as a telephony system, there are the basic telephony services (e.g. call origination, call delivery, call clearing, emergency call, etc.) and the supplementary services (e.g. call waiting, call forwarding, conference-calling, calling number identification, etc.). In addition, as in the wired systems, the features such as custom calling features, Centrex features can be supported by the switch [4,6]. If the air-interface provides a transparent channel to the switch, these service features depend totally on the switch functions. So, we hereafter focus on the wireless transceiver functional blocks as well as on the various WLL system technologies rather than the service features provided for by the switches.

1.4.1 Wireless Transceiver Functional Blocks

Thanks mostly due to cellular systems and their penetration worldwide, the wireless transceiver has reached progress levels, which otherwise would be considered intangible. Advances in the areas of antennas, modulations and *digital signal processing* (DSP) have accelerated the design of wireless transceivers into higher levels of functionality, efficiency and signal quality. Below, we distinguish the functional blocks, which a wireless transceiver consists of. We have the chance to present some issues regarding each such functional block.

Antennas Spatial diversity receive antennas are used to combat the flat fading. Directive antennas with a few degrees of beamwidth are generally sufficient to drastically reduce the delay spread, with the drawback of complete outage of transmission if it exists only in a *non-line-of-sight* (NLOS) path. The second drawback is that it can be used only with temporary fixed terminals unless adaptive phase arrays or switchable antennas are used.

Modulators In wireless communications, the decision upon which modulation will be used is very critical. It is not only the capacity that must be offered within the reserved frequency spectrum but also the resistance it has to exhibit to the various types of interference and noise that characterize the wireless channel. The rapid progress in cellular/mobile and *personal communication services* (PCS) has boosted research in this area. First modulations to be adopted in cellular as well as in cordless systems were $\pi/4$-DQPSK (IS-54, Personal Digital Cellular PDC) and *Gaussian Minimum Shift Keying* (GMSK) (*Global System for Mobile communications* GSM). They proved to be the best candidates for the wireless channel where multipath propagation, cochannel interference, fading and shadowing apart from additive noise and intersymbol interference mostly in TDMA dominate. The success of mobile communications has led a whole class of research teams to work upon the standards of the third-generation systems that among the others they will have to support higher data rates. At the same time, new wireless communication systems thrive to find a trade-off between the higher baud-rate and the most efficient data compression keeping the signal quality at acceptable levels. When, however, the baud-rate increases, the multipath effects are intensified. One solution to combat these effects is to increase the symbol length so that it becomes only a fractional time of the mean delay spread. This can be achieved by using either M-ary modulation types (such as B-O-QAM and Q-O-QAM) or multicarrier modulation (such as *offset frequency-division multiplexing*, OFDM), with the drawbacks of increased hardware complexity, increased transmitted power levels, and high-amplitude linear microwave power amplifiers. Alternatively, *direct sequence spread spectrum* (DSSS) resolves the different delays by correlation techniques. However, since digital correlators are generally limited to a few tens of megahertz, and the sequence length has to be greater than 10 to 100 chips, this solution is not always feasible for high data rate transmission even for the case of indoor communications, where the delay spread is on the order of 10–80 ns.

Filters It is one of the operations cited to be ideally suited for DSP applications. FIR filtering is a repetitive process performed by multiplying the set of input signal samples with a fixed set of known filter coefficients. In the example of IS-136 (TDMA), pulse shaping is done at a transmitter with a square-root raised cosine filter, and appropriate matched filtering has to be done at a receiver. Although straightforward, there are instances when care needs to be exercised to make sure that filtering is executed within the minimum possible number of machine cycles.

Receiver Synchronization Circuits There exist several layers of synchronization [10]:

— Frequency synchronization
— Carrier recovery for coherent demodulation
— Symbol timing recovery
— Slot and frame synchronization

Most synchronization methods require that they be accomplished through initial acquisition, tracking, and reacquisition. Synchronization of frequency is typically accomplished through the use of *automatic frequency control* (AFC). In digital receivers, the received signal constellation rotation is monitored in a DSP and a phase error based measurement is differentiated and filtered. This error signal is used in a digital VCO to come up with a number, which will correct the operation of an analogue component (VCXO). From the DSP this control signal can be sent through the dedicated D/A to a digitally controlled device or converted to a pulse-width modulation form suitable for transmission as an analogue signal. Algorithms for frequency synchronization are often feedback-based and require the operation of the PLL suitable for DSP implementations. Carrier recovery is associated with coherent receivers, where knowledge of the phase of the received signal is required. It is simple to implement a fully digital phase correction algorithm in DSP firmware, again by monitoring the phase error in a signal constellation. It is the decision of implementers if the phase correction is done in the analogue component based on a digital control signal or fully digitally implemented.

In the example of IS-136, frame timing is the first synchronization that can be accomplished using training symbols at the beginning of all data frames. Frame synchronization is accomplished by correlation of the received waveform with the replica of the training waveform(s) known to the receiver. This is the feed-forward type of operation. The receiver repetitively correlates the signal until it identifies a peak in the correlation function, and based on the peak's location in time adjusts its timing. It is important to note that in cases where a frequency offset exists the correlation will fail when it is done only against the ideal original training waveforms. For good performance in realistic environments it is also necessary to correlate the received signal against frequency-shifted original waveforms. A typical DSP is ideal for correlation operations. Tracking of the frame timing can be accomplished by the same operation, except that the span of the received signal, which needs to be correlated, is significantly smaller since we are close to the actual timing. Here, though, one has the choice of implementing better resolution.

Symbol timing recovery makes sure that a received signal waveform is sampled as close as possible to the optimal sampling point for detection. Since it is desirable to have A/D converters operate at the slowest possible rate, it is required to be able to finely change the sampling position. Indeed, one can choose to adjust the sampling phase of an A/D explicitly. However, more and more often in digital receivers, the preferred choice is to let the converter keep sampling at an arbitrary phase and to use digital interpolation to find the value of the signal at the optimal sampling point from two or more neighbouring samples of an arbitrary phase.

Equalizers The fact that wireless channels have an associated delay spread which causes intersymbol interference requires in some instances that this be compensated for. However, the higher the symbol rate is, the more complex and time- and power-consuming the device is. For a 24.3 kbps IS-136 system, the delay spread which causes trouble and requires an equalizer is on the order of $10\,\mu s$. Two principal techniques are used for equalization: *decision-feedback equalizers* (DFEs) and *maximum-likelihood sequence estimator*s (MLSEs). Equalization is one of the most MIPS-intensive functions in cellular phone receivers. Although equalizers are not always needed, since channels often have smaller delay spreads as happens in WLL, receivers/DSPs have to be designed to be able to handle equalization. DFEs consist of two FIR filters and are amenable to DSP implementations. MLSE equalization requires clever memory addressing approaches, which DSPs support.

Channel Coders/Decoders Channel coding is almost always applied in cellular/WLL communications systems. FEC (*forward error correction*) codes and interleaving techniques (to randomize the errors) are used to correct a certain number of bit errors, thus giving a coding gain (relative to the received power). However, this has the drawback of needing an increased transmitted bit rate, leading to higher levels of ISI and creating more decoding delays and complexity due to the necessary interleaving memories. The operation of coding is always simpler than decoding. Both block-code and convolutional-code decoding can be demanding in terms of the number of cycles required. DSP vendors are paying particular attention to efficient software implementations and/or building specialized hardware for trellis search techniques, which are effective for various decoding schemes. These accelerators are probably the first of a number of accelerators that will deal with speeding up the operation of DSPs. It is interesting to note that Viterbi MLSE equalization techniques can sometimes share trellis-searching structures with channel code decoders. This is most obvious in GSM, where modulation is binary.

Automatic Gain Controllers While propagating through a wireless channel, a signal can experience dramatic changes in power levels. Standard deviation of a signal due to shadowing is on the order of 8–12 dB, whereas Rayleigh fading can cause as much as 30–40 dB of rapid signal power fluctuations. It is not always desirable to get rid of all Rayleigh fading fluctuations (especially when they occur rapidly), but shadowing needs to be compensated for. Automatic gain control schemes in modern receivers collect and process data in the digital domain, and then send control information to analogue components, which adjust, signal power levels prior to A/D converters. It is not usual to have overdesigned A/Ds (in terms of the number of bits), which would let DSPs cover most of the dynamic range of radio signals.

1.5 WLL System Technologies

Early WLL systems used standard cellular and cordless technologies to gain access to spectrum. These are at low frequencies, which have become congested and expensive, as mobile operators are able to pay premium rates. In our days, however, WLL deployments also utilize other proprietary systems, narrowband or broadband in frequency bands that have been provided by ITU on a worldwide basis. In general, the frequency bands, which have been used or standardized for WLL service, are described in Table 1.2.

1.5.1 High-Range Cellular Systems

The high-range cellular systems support high mobility and can be characterized by the wider coverage with relatively low data rate. These systems include the second-generation digital cellular systems using 800 MHz band (e.g. IS-95A, and GSM) and their up-banded variations for the personal communications services (PCS) using 1.8–2.0 GHz band (for example, W-CDMA and IS-95B as an up-banded version of IS-95A, and DCS-1800 as an up-banded version of GSM). Since cellular systems are capacity limited due to the limited spectrum resources, they have turned to efficient multiple access techniques such as TDMA and CDMA. Although these two techniques are more efficient than FDMA, it is difficult to say which one is superior. Appendix B touches properly this matter.

Table 1.2 Frequencies used or standardized for WLL

Frequency	Use
400–500 MHz	Rural applications with mostly analogue cellular systems
800–1000 MHz	Digital cellular radio in most countries
1.5 GHz	Typically for satellites and fixed links
1.7–2 GHz	Cordless and cellular bands in most countries
2.5 GHz	Typically for Industrial, Scientific and Medical (ISM) equipment
3.4–3.6 GHz	Standardized for WLL around the world
10 GHz	Newly standardized for WLL in some countries
28 GHz and 40 GHz	For microwave distribution systems around the world

Among the above-mentioned systems, we briefly outline TDMA (IS-136, GSM), and CDMA (IS-95A, IS-95B, W-CDMA) systems [11].

1.5.1.1 TDMA (IS-136/GSM)

TDMA is a narrowband system in which communications per frequency channel are apportioned according to time. For TDMA system, there are two prevalent standards: *North American Telecommunications/Electronics Industry Association* (TIA/EIA) IS-136 and *European Telecommunications Standards Institute* (ETSI) Global System for Mobile Telecommunications (GSM). The IS-136 and GSM standards use different modulation schemes (i.e. $\pi/4$-QPSK for IS-136 and GMSK for GSM). Also, the channel bandwidth of the two systems is different (30 kHz for IS-136 and 200 kHz for GSM). GSM has a frame length of 4.615 ms instead of 40 ms for IS-136. The operational frequencies of these TDMA schemes differ and only GSM supports frequency hopping. GSM uses *Regular Pulse Excitation Long Term Predictive* (RPE-LTP) voice coding algorithm at full rate of 13 kbps or half-rate 6.5 kbps and Enhanced Full Rate at 12.2 kbps whereas IS-136 uses Vector Sum Excited Linear Predictor VSELP at 8 kbps, IS-641-A at 7.4 kbps and US1 at 12.2 kbps. The maximum possible data rate achievable is 115.2–182.4 kbps with General Packet Radio Service supported from GSM and 43.2 kbps for IS-136+. They both use hard handover.

1.5.1.2 CDMA (IS-95A, IS-95B, W-CDMA)

CDMA (IS-95A) is a direct sequence spread spectrum (DSSS) system where the entire bandwidth of the system 1.25 MHz is made available to each user. The bandwidth is many times larger than the bandwidth required transmitting information. In CDMA systems *pseudonoise* (PN) sequences are used for the different user signals with the same transmission bandwidth. For IS-95, a frame length of 20 ms has been adopted. Regarding vocoders, it uses Qualcomm Code Excited Linear Prediction QCELP at 8 kbps, CELP at 8 kbps and 13 Kbps. Compared to the TDMA counterparts, it uses soft handover and either QPSK or O-QPSK as the modulation format.

IS-95-A [12] standard has been developed for a digital cellular system, operating at 800 MHz band. ANSI J-STD-008 [13] being an up-banded variation of IS-95 is a standard for PCS systems, operating at $1.8 \sim 2.0$ GHz band. Recently, IS-95-B [14] merges IS-95-A and ANSI J-STD-008.

IS-95 based CDMA WLL can support two rate sets. A code channel (that is, a traffic channel) operates at maximum of 9.6 kbps with the rate set 1 or 14.4 kbps with rate set 2. Using rate set 1 (rate set 2), the system supports 8 kbps (13 kbps) *Qualcomm's codebook excited linear predictive* (QCELP) vocoder.

IS-95B offers high-rate data services through code aggregation. In IS-95B systems, multiple codes (up to eight codes) may be assigned to a connection. Thus, the maximum data rate is 76.8 Kbps using rate set 1 or 115.2 Kbps, using rate set 2. Since IS-95B can be implemented without changing the physical layer of IS-95A [15], it is relatively easy for the vendor of IS-95 WLL system to develop the IS-95B WLL system.

In mobile IS-95 systems, a sectored cell is designed with three sectors in usual. As mentioned above, in WLL systems, the antennas for BTS and FSU can be arranged by line-of-sight and this reduces interference from the other user. So, the CDMA WLL cell can be designed with six or more sectors [6]. This increases the frequency efficiency and the system capacity.

Both IS-95A and IS-95B have some limitations in supporting high-rate data or multimedia services because of the insufficient maximum data rate per channel. An alternative technology to cope with this problem is the *wideband CDMA* (W-CDMA) [16]. In comparison with the existing narrowband CDMA systems, W-CDMA systems use higher chip rate for direct sequence spread spectrum and, thus, spread its information into wider spectrum bandwidth (typically, equal to or over 5 MHz). Thus, data rate per code channel in W-CDMA can be higher than that in IS-95 systems. Note that all of the major candidates for *radio transmission technology* (RTT) of the *international mobile telecommunications-2000* (IMT-2000) systems have proposed W-CDMA for next-generation mobile communication systems (e.g. [17–19]).

Below, the technical characteristics and the services of a current WLL deployment based on W-CDMA are described. The downlink (from BTS to FSU) uses the band from 2.30 to 2.33 GHz and the uplink (from FSU to BTS) uses the band $2.37 \sim 2.40$ GHz. Thus, the bandwidth of each link is 30 MHz. The spreading bandwidth can be either 5 MHz or 10 MHz. For both spreading bandwidths, the information bit rates are 8, 16, 32, 64, and 80 kbps. For the case of 10 MHz spreading bandwidth, 144 kbps of information bit rate is also available.

The WLL standard defines several options for voice codec: 64 kbps PCM (ITU-T G.711), 32 kbps ADPCM (ITU-T G.726), 16 kbps LD-CELP (ITU-T G.728), and 8 kbps conjugate structure algebraic-code-excited linear prediction (CS-ACELP, ITU-T G.729). However, the service provider seems to offer voice services using 16 kbps LD-CELP and 32 kbps ADPCM since those give toll quality of voice with adequate system capacity. As the voice-band data services, G3 facsimile and 56 kbps modem is planned.

For packet mode data transmission, some dedicated channels, which are separated from voice channels, are provided. They are the packet access channels in uplink and the packet traffic channels in downlink. Using these channels, packet data services up to 128 kbps are offered. In addition, ISDN BRI is also provided.

1.5.2 Low-range Cordless Systems

The advantage of the high-range radio system is the large coverage area of the base stations and the degree of mobility at which access can be supported. The trade-off, however, is low quality voice and limited data service capabilities with high delays. The low-range systems are disadvantaged in coverage area size and user speeds, which is not so important. The advantages include high-quality, low-delay voice and high-rate data capabilities. In comparison with high-range systems, low-range systems provide more wireline-like services. The range of a WLL, however, can be extended via point-to-point microwave hop using a translator which can up-convert signal frequencies in a spectral band to microwave or optical frequencies, and then down-convert to the signal at the remote cell sites before connecting to WLL terminals or buildings. There are several standards for low-range systems. The representative examples are the *digital enhanced cordless telecommunications* (DECT) [11] and its North American variation *Personal Wireless Telecommunication* (PWT), the *Personal Access Communications System* (PACS), and the P*ersonal Handy-phone Services* (PHS). All these standards adopt the TDMA technology.

1.5.2.1 Digital Enhanced Cordless Telecommunication (DECT/PWT)

DECT is a radio interface standard developed in Europe mainly for indoor wireless applications and being deployed for WLL applications as well during the last years. Personal Wireless Telecommunications (PWT) is a DECT-based standard developed by the *Telecommunications Industry Association* (TIA) in the United States for unlicensed personal communications services (PCS) applications. PWT-Enhanced is the version, that is suitable for licensed PCS applications [20].

DECT originally supports small cells (radius of $100 \sim 150$ m) with pedestrian-speed mobility [21]. To use DECT in WLL applications, one of the most important problems to be solved is to extend the maximum coverage of a fixed part (i.e. BTS). A solution is to use directional antennas, by which the maximum diameter of a cell can be extended up to several kilometers. For rural applications, using repeaters at the expense of capacity can extend the coverage [8].

The basic unit of channel in DECT is a time slot per TDMA frame, operating at 32 kbps. If data rates higher than 32 kbps are required, multiple time slots per frame are used. Otherwise, if the requested data rate is lower than 32 kbps, several FSUs can share a 32 kbps channel by skipping time slots. DECT offers toll quality digital speech and voice-band modem transparency either via a 32 kbps ADPCM codec (ITU-T G.726) or as a 64 kbps PCM (ITU-T G.711) bearer service [22]. DECT provides up to 504 Kbps full duplex data transfer and of course BRA ISDN [23]. Since all user information is encrypted, there is confidentiality between the different users belonging to a same cell. DECT has signalling compatibility with basic ISDN and GSM. For more detailed aspects of DECT WLL, one can refer to ANSI J-STD-014 [24].

For Europe, DECT uses Gaussian minimum shift keying (GMSK) with a bandwidth of 1.728 MHz and 12 time slots per carrier. DECT does not efficiently utilize the unlicensed and 10 MHz licensed bands in the United States. Therefore, the protocol was modified to use $\pi/4$ quadrature phase shift keying ($\pi/4$-QPSK) which allows more efficient use of the spectrum.

While other PCS technologies separate the band into a handset transmit band and a base station transmit band (FDD), PWT uses *time-division duplex* (TDD) with both the handset and base station transmitting on the same frequency (at different times). PWT has 24 time slots in 10 ms. Twelve slots are defined for base-to-handset transmission, and 12 are defined for handset-to-base transmission. The overall data rate for voice for handset/base is 32 kbps using *adaptive differential pulse code modulation* (ADPCM), which provides toll-quality voice. The transmission path between handset and base station uses a pair of time slots on the single RF channel.

PWT uses *dynamic channel allocation* (DCA) to assign frequencies to the channels; as the name implies, the frequencies are allocated right before their use. The DCA mechanism provides efficient use of the valuable radio spectrum. The size of the cell covered by an RFP is rather small, less than 150 m for urban applications and 1–2 km for rural applications. For rural applications the coverage can be extended by using repeaters at the expense of capacity. DECT is primarily designed to support pedestrian-speed mobility. This speed is typically less than 10 km/hr.

1.5.2.2 Personal Access Communication System (PACS)

PACS employs TDMA/TDM on the radio interface using $\pi/4$-QPSK modulation at a symbol rate of 192 Kbaud [7–8,25–26]. The radio frame is 2.5 ms in duration with

8 bursts/frame. PACS uses *International Telecommunications Union-Telecommunications Standardization Sector* (ITU-T) standard 32 kbps ADPCM speech coder and can maintain very good voice quality with two or three speech coders in tandem. Optionally, 16 Kbps *low-delay code-excited linear prediction* (LD-CELP) being defined as ITU-T G.728 can be used.

For voice-band data, PACS provides 64 Kbps *pulse code modulation* (PCM) connection (ITU-T G.711) by aggregating two time slots. This service is used to support all voice band modems including 56 Kbps modems. PACS supports circuit mode and packet mode data services. In addition, individual message service and interleaved speech/data service are also provided.

- *Circuit-mode data service*: PACS offers reliable real-time data transport service using *link access procedure for radio* (LAPR). LAPR operating in a 32 Kbps channel provides a data throughput of more than 28 Kbps at wireline error rate (10^{-6}).
- *Messaging services*: This is two-way point-to-point message service for large file transfer up to 16 Mbytes. The messages can contain text, image, audio, and video files.
- *Packet-mode data service*: This is a shared, contention-based, RF packet protocol using a data sense multiple access contention mechanism. It supports FSU by using single time slot (32 Kbps) or multiple time slots (up to 256 Kbps) per TDMA frame. The applications being suitable over the PACS packet channel are wireless Internet access and mobile computing, etc.
- *Interleaved Speech/Data*: It provides the ability to transmit both speech information and data information by using a single 32 Kbps time slot. Data is transmitted during the silent period of voice.

Low-power PCS systems, such as PACS, require radio port (RP) operating frequencies to be assigned automatically and autonomously, eliminating the need for manual frequency planning. The automatic frequency assignment in PACS is called *quasi-static autonomous frequency assignment* (QSAFA). QSAFA is a self-regulating means of selecting individual RP frequency channel pairs that function without a centralized frequency coordination between different RPs.

PACS uses *frequency-division duplex* (FDD) for the licensed version and TDD for the unlicensed version. The specification of PACS allows for low-complexity implementations of both *subscriber units* (SU)s and radio ports (RP)s in order to reduce wireless access system costs and network costs. SU peak transmit power is 200 mW, and the average power is 25 mW. The RPs function largely as RF modems, depending on the centrally located RPCUs for most of the functionality traditionally associated with port electronics.

In PACS, the SU determines when and to which RP to perform *automatic link transfer* (ALT) or handoff. The ALT decisions are made by the SU in order to offload this task from the network and to ensure robustness of the radio link by allowing reconnection of calls even when radio channels suddenly become poor. The SU first measures the radio signals. If certain criteria are reached based on the measurements, ALT is performed. The SU determines the new RP for ALT and executes the transfer with the network. FDD provides an advantage over TDD in handling port-to-port synchronization. In TDD operations, both the uplink and downlink of a channel use the same frequency. This requires that RPs be synchronized in order to minimize the interference from each other. In FDD operations, uplink and downlink are on different frequencies. This results in better interference management and does not require adjacent port synchronization, which helps reduce the RF cost of the equipment. The frame delay in PACS is about 5 ms. Such a very low delay negates the need for an echo canceller circuit in the radio equipment. In PWT and other radio technologies, an echo canceller is typically required [8–9].

There are two types of user terminals in PACS/WLL: portable handset (subscriber unit) and fixed access unit. The fixed access units convert the radio signal to a RJ-11 interface signal to the customer premises equipment. The user terminal communicates with the radio port following the JTC/PACS air interface (TDM/TDMA at the 1850–1910 MHz and 1930–1990 MHz frequency bands). The coverage area of a radio port (RP) is 0.5–2 km for the portable handsets and more than 2 km for the fixed access units. The RP connects to the radio port control unit (RPCU) by E1, T1, HDSL, or DSL technologies.

1.5.2.3 Personal Handyphone System (PHS)

PHS is a low-range personal communications services (PCS) technology that was developed in Japan by a consortium of companies to support very-high-density pedestrian traffic and WLL. It is built on a foundation of digital cordless technology and microcell architecture.

PHS uses $\pi/4$-DQPSK in the RF band of 1900 MHz as DECT with a bandwidth of 300 KHz per channel. Each channel consists of either 3 or 4 time-slots. However, it has a better spectrum efficiency than DECT since it has 4 time slots per 300 KHz carrier instead of 12 slots per 1.728 MHz carrier. The multiple access scheme used is TDMA/TDD and the voice coding is 32 kbps ADPCM. PHS makes use of Dynamic Channel Assignment and is more flexible in network planning and more cost-effective and suitable for WLL. Due to its architecture, it is less sensitive to multipath and delay and has bigger cell coverage. In urban areas, it uses 5 times fewer base transmission stations than DECT when covering the same area, whereas in rural areas PHS has a wider service coverage than DECT since it is more tolerant of delay spread.

PHS *personal stations* (PSs) consist of handheld units that can operate as simple cordless phones, as transceivers for communications with other personal stations, or as mobile terminals to access the *public switched telephone network* (PSTN). The mode of operation must be selected by the user. The *cell station*s (CSs) handle the control and transmitter functions. The CS consists of the antenna and the base station unit. Its output power ranges from 100 mW to 500 mW according to the number of users in the area to be served. CSs are usually mounted on utility poles, payphone boxes, and roofs. The CS is connected to the fixed network with integrated services digital network (ISDN). The control station is essentially a database unit for storing subscriber data.

1.5.3 Proprietary Narrowband WLL

The number of competitors in the local loop and service capability, influences likely penetration, and hence capacity and range requirements of the technology solution. Among the several WLL systems already in use in various markets, we outline the TDMA proprietary systems E-TDMA of HNS and Proximity I/II of Nortel, the CDMA proprietary systems QCTel of Qualcomm, Airloop of Lucent and Airspan of DSC, and finally the FH-CDMA/TDMA system Multigain of Tadiran.

1.5.3.1 HNS E-TDMA

E-TDMA [27] is an extension to the IS-136 cellular TDMA standard that provides support for WLL with increased capacity and improved network performance while maintaining the large coverage area feature of other cellular standards. E-TDMA offers a choice of subscriber unit platforms including *single subscriber units* (SSU) and *multiple subscriber units* (MSU) capable of supporting up to 96 lines, depending on the subscriber traffic load and MSU provisioning. The single subscriber units support high-capacity digital voice, fax, and data transparently using a standard RJ-11 interface, and enable multiple terminal connections as simple extensions on a single access unit or per directory number. Such units are appropriate for locations with low population densities such as residences and small businesses. Multiple subscriber units provide access to the WLL system in areas of high population densities such as hotels and apartment buildings. MSU and radio resources are allocated on a call-by-call basis, thereby reducing the required hardware.

The E-TDMA base station provides an improved control channel to dynamically assign channels and time-slots to active speakers. A 5 kbps rate voice coder is also used which more than doubles the capacity over IS-136. Finally, the implementation of *discontinuous transmission* (DTX) along with *digital speech interpolation* (DSI) means that both the base station and the subscriber station transmit only when speech is present (about 40 percent of the time), thus sharing the radio resource effectively with other users. E-TDMA supports a wide variety of country variant signalling. Tones and line signalling variations are software programmable, and in a number of cases can be set via system parameters. Both 16 kHz metering and Polarity reversal signalling mechanisms for pulse signalling can be supported, if they are generated and supported by the switching system. Thus, E-TDMA can interface with a wide variety of metering and public pay phone equipment. Depending on the subtending switching equipment, E-TDMA is capable of supporting virtually all of the vertical features and CLASS features recommended by TR-45, as listed above, including call waiting, call forwarding, conference calling, and so on. The main strengths of cellular-based WLL systems over low-range PCS based WLL systems include coverage, speed of deployment, and spectrum efficiency. The fundamental disadvantage is the limited range of available user bandwidth. This trade-off implies a market for both system types.

1.5.3.2 Nortel Proximity I/Proximity II

Nortel makes a class of narrowband WLL systems under the banner Proximity which are not based on cordless or cellular technologies. Proximity I is a proprietary TDMA system developed in conjunction with the United Kingdom WLL operator Ionica, one of the first operators in the world to deploy a proprietary WLL system. Proximity I offers a wide range of services, including 64-kbps voice and data links and a second-line capability. Subscriber units link to base stations over the air-interface, and base stations then are connected directly back to a PSTN switch.

Proximity II is an upgraded version, that is more flexibly tailored to suit each individual operators' requirements—from small city based systems supporting a few thousand customers up to large nationwide systems with capacities in excess of one million. Proximity II provides also BRA ISDN service and enables high-rate Internet access at 128 Kbps. Its compact base station has a capacity of 2000 lines and it may be located up to 40 km from the users. The user premises equipment supports one or two lines for PSTN or ISDN terminals. Its System Management is compatible with public network switches through V5.2 signalling.

Both system versions use TDMA channels of bandwidth 3072 kHz in a cluster size of 3, and *quadrature phase shift keying* (QPSK) modulation format. Up to 54 TDMA bearers can be accommodated in the 3.4–3.6 GHz assignment using frequency division duplex (FDD) either 50 or 100 MHz with a maximum of 18 channels on any given base station. DCA is not provided, but it is relatively easy to reconfigure the frequency assignment from the operations and maintenance centre.

1.5.3.3 Qualcomm QCTel

Qualcomm's QCTel CDMA WLL System is a Fixed Wireless Access WLL [28]. A basic six-sector QCTel system may support 24 000 subscribers. The QCTel technology supports 8 kbps voice and up to 7.2 kbps data rate. QCTel supports limited mobility, and the subscriber unit can be a portable handset. The handset communicates with the base station transceiver using the IS-95 air-interface (CDMA/FDD at the 800 MHz, 900 MHz, and 1.8–2.2 GHz frequency bands). The handset can support multiple lines. The transmit power is 2 W (with power control).

The base transceiver station (BTS) communicates with the handset using the IS-95 air-interface. The maximum transmit power is 50 W. The cell range is 25 km. The capacity is up to 45 voice channels. Up to 20 BTSs may be collocated with the base station controller (BSC) at the central office. Or 30 BTSs per area may be connected to a BSC using the T1/E1 technology (up to three areas). The BSC is collocated with a central office, which connects to a switch of the PSTN using T1, E1, T3, or E3 digital multiplexed trunks. The call control is done by R2 inband signalling, and the OMC signalling is done by SS7 or X.25.

1.5.3.4 Lucent Airloop

The Lucent Airloop technology is another proprietary CDMA-based system developed for a wide rank of customers. It operates mainly in the 3.4-GHz band using 5-MHz wide channels, each supporting 115 16-kbps channels. To support 32-kbps ADPCM, two channels are used simultaneously. The spreading code is 4096 kbps; thus, for a 16-kbps data rate, a spreading factor of 256 is used. The system employs a network of *radio base stations* (RBSs) to provide coverage of the intended service area. The main functional blocks of the network are the following:

- *Central Office* (CO): It contains digital switching and network routing facilities required connecting the radio network to ISDN and the Internet.
- *Central Access and Transcoding Unit* (CATU): It controls the allocation of radio resources and ensures that the allocation is appropriate to the service being provided, for example, 64-kbps digital, 32-kbps speech, ISDN. It also provides transcoding between various speech-coding rates and the switched 64-kbps PCM.
- *Central Transceiver Unit* (CTU): It provides the CDMA air-interface. It transfers ISDN and *plain old telephony* (POTS) signalling information transparently between the air-interface and the CATU.
- *Network Interface Unit* (NIU): It connects the subscribers to the radio network through two functional blocks, the *intelligent telephone socket* (ITS) and the *subscriber transceiver unit* (STRU).

- The ITS provides the point of connection to the subscriber's terminal equipment, for example, PABX, telephone, or LAN.
- The STRU is located on the outside of the subscriber's building and consists of an integrated antenna and radio transceiver. The STRU provides the interface between the ITS and the CDMA air-interface. The STRU is connected to the ITS by a standard four-wire telephone or data networking cable.

The type of service being provided by the connection determines the number of subscriber connections supported by each NIU. The basic NIU connection provides a single ISDN (2B + D) connection, effectively giving two unrestricted 64-kbps channels. The same unit also can he configured as either two or eight individual POTS lines using ADPCM and *Code excited linear predictive* (CELP) speech coding, respectively.

The modulation technique employed first takes each 16-kbps channel and adds error-correction coding to reach 32 kbps. It then uses Walsh spreading with a spreading factor of 128 to reach the transmitted data rate of 4 Mbps. Finally, it multiplies that by one of a set of 16 PN code sequences also at 4 Mbps, which does not change the output data rate but provides for interference reduction from adjacent cells. During design of the network, each cell must have a PN code sequence number assigned to it such that neighbouring cells do not have the same number.

1.5.3.5 DSC Airspan

The DSC Airspan system was developed in conjunction with BT, which is using the system for rural access at 2 GHz. The system provides 64-kbps voice channels and support for up to 144 kbps ISDN services. DSC claims a cluster size of between 1 and 3, depending on the environment. Voice currently is provided using 64-kbps PCM and ADPCM at 32 kbps. The system currently provides 2B + D ISDN per subscriber or, alternatively, 2×64 kbps data channels. Up to 6×64 kbps data channels can be achieved by combining three subscriber units.

Radio channels are 3.5 MHz wide. Each 3.5-MHz channel provides up to fifteen l60-kbps radio bearers. With the current deployment, each 160-kbps bearer can provide two 64-kbps voice-channels or four 32-kbps voice channels, each to a different house.

1.5.3.6 Tadiran Multigain

Tadiran markets its proprietary system as FH-CDMA/TDMA. In the Tadiran system, users transmit in a given TDMA slot. However, the actual frequency in which they transmit changes from burst to burst, where a burst lasts 2 ms (hence, there are 500 hops/s). In a given cell, no two users transmit on the same frequency at the same time. However, users may transmit on the same frequency in adjacent cells. By employing different hopping sequences in adjacent cells, if a collision does occur it will be only for a single burst. Error correction and interleaving largely can overcome the effect of such a collision. The system has the advantages of the simplicity of a TDMA system coupled with some of the 'interference-sharing' properties that make CDMA spectrally efficient. Tadiran claims that a cluster size of 1.25 can be achieved by that approach when directional antennas are deployed. In practice that seems somewhat optimistic, and it might be expected that a cluster size of 2 would be more realistic.

The system uses a voice coder of 32 kbps. It employs TDD, in which both the uplink and the downlink are transmitted on the same frequency but at different times. Each 1×1 MHz channel supports eight voice channels. Hence, 16 voice channels per 2×1 MHz can be supported before the cluster effect is taken into account, and assuming a cluster size of 2, around 8 voice channels/cell/2×1 MHz.

1.5.4 Proprietary Broadband WLL

A number of systems have been proposed and implemented that use WLL techniques to deliver broadcast TV [29]. Such systems fall into a niche somewhere between terrestrial TV broadcasting and WLL telephony delivery. They offer advantages over terrestrial TV broadcasting in that they can provide many more channels and may offer advantages over the other WLL systems discussed here in their ability to deliver high-bandwidth services. Broadly speaking, the only difference between WLL and microwave distribution is that the latter tends to be transmitted at much higher frequencies, such as 40 GHz, where significantly more bandwidth is available and hence wider bandwidth services can be offered. However, such higher frequencies result in lower propagation distances and more costly equipment. Further, rain fading can be a significant problem in some regions at such frequencies, making reception unreliable.

The first microwave distribution systems were implemented in the United States, where they were called *microwave multipoint distribution systems* (MMDS). The systems tended to operate between 2.15 GHz and 2.682 GHz and provided a maximum of 33 analogue TV channels to communities at a bandwidth of 500 MHz. They were entirely broadcast systems, and no return path capability was provided. However, compared to cable TV and satellite systems that support 30–60 and 150–200 video channels respectively, MMDS operators had to resort to digital compression techniques to become competitive. Many such systems are still in existence between 2.5 and 3 GHz, but with the introduction of digital broadcasting they will become increasingly outdated.

After MMDS, digital distribution systems operating at around 29 GHz were introduced in the United States and the Asia–Pacific countries. The systems, known as *Local multipoint distribution systems* (LMDS) [30], can provide many more channels with a higher quality but lower range. It is considered as a strong candidate for next-generation *broadband WLL* (B-WLL) services. The spectrum for LMDS differs from country to country but it is usually in the $20 \sim 30$ GHz band. The LMDS applications include a variety of multimedia services such as POTS, ISDN, *broadband ISDN* (B-ISDN), television program distribution, videoconference, VOD, teleshopping, and Internet access. LMDS can offer two-way wireless services, whereas MMDS and satellite systems require terrestrial wired networks to communicate back to the headend, for example, to select programming or use VCR-type controls on *video-on-demand* (VOD) programming.

The primary disadvantages of both the MMDS and LMDS are cochannel interference from other cells and limitations on coverage (up to 25 miles for MMDS and up to 5 miles for LMDS) [31]. Millimetre-wave radio signals do not penetrate trees. Thus, line-of-sight propagation paths are required. This requirement can make antenna placement on subscriber homes challenging. Despite, however, the fixed locations of both transmitter and receiver, the influence of motion of traffic and foliage, even in a line-of-sight location, creates a fading environment, which is much more hostile than measured for conventional cellular mobile systems, at say, 2 GHz. Temporal fades of over 40 dB at the rate of at most a few (< 2) hertz are frequently seen in these environments, imposing very stringent requirements on the error correction coding of the transmitted bitstream.

Another serious problem in wireless multimedia services is traffic asymmetry between uplink and downlink [16–18,32]. For example, let us consider Internet access or remote computing. In these applications, short commands are transmitted via uplink, whereas relatively large files are transmitted via downlink. In these cases, if both links have the same bandwidth, the system capacity can be limited by the downlink. This, in turn, results in bandwidth waste of uplink and, eventually, spectrum inefficiency. To cope with traffic unbalance, the spectrum allocation for LMDS is given to be asymmetric between uplink and downlink. Since LMDS is a FDD system, the downlink bandwidth should be appropriately wider than the uplink. Another solution for this is to use time division duplex (TDD) between two links. Thus, CDMA/TDD systems, having both the merits of CDMA (e.g. in capacity) and the advantages of TDD (e.g. flexibility in resource allocation), have been attracting many researchers' attention recently [16–18].

Similar initiatives in the United States and Europe have lead to the system operating at 40 GHz, *Microwave Video Distribution System* (MVDS). Early in the development process of MVDS, it became apparent that to provide competition to cable and to maximize the revenues that could be achieved, a return path from the home to the network would be required. That allows voice and limited data enabling, for example, selection of video films. Systems capable of providing such a return path are now in a trial stage. The return path can provide around 20 kbps of data.

MVDS systems still are relatively immature, so it is difficult to provide significant amounts of information on particular products. It can be seen that in terms of telephony provision, MVDS is inferior to other WLL systems. However, when telephony is viewed as a service offered on the back of video distribution, it looks more attractive. It is too early to say whether the economics of MVDS will allow the telephony component to be sufficiently cheap so that users will accept its relative shortcomings. However, for many users, telephony is a critical service that they will not compromise to realize some savings. Hence, at least for the next few years, it is unlikely that microwave distribution systems will provide an acceptable WLL service. Instead, they provide a wireless alternative for the cable operator.

1.5.4.1 HNS AIReach Broadband

AIReach Broadband constitutes a powerful platform for offering fibre-quality 'last-mile' wireless solutions that encompass voice, video, data, multimedia, and Internet services. It aims at serving either individual business customers or multitenant offices/residential complexes. The AIReach Broadband product family consists of two product series. One is ideally suited for semi-urban or light to medium urban areas whereas the other is suited for medium to high-density urban areas. They both address the small to medium size business customers and *multidwelling unit*s (MDUs) and they operate either in the ITU/ETSI frequency bands: 3.5 GHz, 10.5 GHz, and 24–26 GHz or in the frequency bands between 24–42 GHz. The maximum data rate achieved per carrier is 4 Mbps and 45 Mbps respectively.

AIReach Broadband system can start with a single radio at the hub and as few as two subscriber terminals though a completely scaleable hub. It uses 64-QAM as modulation format achieving one of the highest spectral efficiencies available. Moreover, the high-capacity product series deploys *Tri-Mode Modulation* (TMM), which enables balance between coverage and capacity, since with TMM, a single hub radio can switch modulation modes on a burst-to-burst basis.

AIReach Broadband assigns bandwidth on demand as well as voice and data concentration via dynamic bandwidth management making the economics very competitive to wireline solutions. Outdoor terminals take up less rooftop space and provide better installation options. Small indoor terminals with easy front access for all of the cabling are designed for tight spaces and cluttered environments in telecom closets. The low-capacity product series offers the following services and interfaces: E1; N $\times$ DS0; Ethernet and Frame Relay; services with BoD; V5.2; Internet Services; BRA ISDN; ATM; 10 BaseT; V35/X.21. Additionally, the high-capacity product series offers: N $\times$ T1/E1; LAN; ATM; 10/100 BaseT; PRA ISDN; MPEG2.

1.5.4.2 Motorola SpectraPoint

SpectraPoint has a strong headstart in the direction of facilitating multiplatform integration via IP and ATM, having been working with Cisco Inc. for most of the last few years to integrate router switches and other IP components into the LMDS access system. SpectraPoint already integrates its product series with software, which supports dynamic changes in modulation from the more robust, low bits-per-Hertz levels to the noise-sensitive, high-capacity levels as weather conditions change or customers shift the trade-offs they want to make between bandwidth efficiency and quality of service.

The air-interface of the SpectraPoint platforms already supports QPSK (quadrature phase shift key) and 8, 16 and 32 QAM (*quadrature amplitude modulation*) modulation formats as well as Viterbi and Reed Solomon as Forward Error Correction methods. Frequency re-use is enhanced via polarization diversity (factory-selectable horizontal or vertical). The channel spacing is 40 MHz allowing for a 45 Mbps downstream speed and a 2 up to 10 Mbps upstream speed. The average transmitted power is 1 W for the base station and 100 mW for the subscriber unit.

One of the innovations Spectrapoint brings to LMDS fixed wireless products is the ability to transport everything in ATM while using time division multiple access to dynamically alter the amount of bandwidth devoted to any one user's needs. This way, all the users on a single RF LMDS channel, which now supports up to 45 Mbps and in due course 155 Mbps, can pay for services on an as-needed basis, allowing service providers to more efficiently allocate bandwidth, that is not in use from one moment to the next.

1.5.4.3 Nortel Reunion

Reunion is another *point-to-multipoint* (PMP) system—also referred to as *broadband wireless access* (BWA). It is similar in design to cellular or narrowband wireless local loop systems, but offers bandwidth connection ranges from 64 Kbps up to 155 Mbps—offering great flexibility in serving local access markets. Reunion's unique Quad-4 architecture exploits the potential of four access technologies to produce exceptional network flexibility and efficiency as well as to provide consistency and congruence with wired networks. The advantage of Quad-4 is that it is able to tailor and optimize the network deployment. Quad-4 makes FDMA, TDMA, ATM, and IP connections possible—all from a single platform.

- FDMA provides efficiency in delivering high volumes of data.
- TDMA's greater spectrum and cost efficiency is suited for low bandwidth and sporadic voice and data needs.

- ATM is an excellent solution for multimedia applications and high Quality of Service requirements.
- IP is the technology of choice for low-cost customer premise equipment and end-user applications to help penetrate the SOHO market.

Reunion portfolio offers High-Rate Data Transfer, LAN/WAN Interconnection, Internet/Intranet Access, Telephony, Voice over IP, Corporate Video Services, Home Banking, Distance Learning, Tele-Medicine, Video Conferencing, VPN, E-Commerce, Web TV, Interactive Gaming, Video Streaming. Reunion can be deployed to handle bundled multimedia services or single service solutions.

The Reunion network architecture consists of the following three major elements:

- The Reunion Base Station, consisting of the *Network Node Equipment* (NNE) and the *Base Station Transceiver* (BTR), facilitates the multiplexing, mapping, modulation, and transmission of multimedia content to and from the access market. This equipment, which operates in a variety of downstream and upstream frequencies between 2 GHz and 42 GHz, offers high-capacity. All of this capacity and performance is packed into a small footprint.
- The Reunion element management system facilitates the operations, administration, maintenance, and provisioning of the network.
- A cost-effective integrated CPE meets the needs of the small- to medium-sized customer, providing up to four E1/T1 and 10 Base-T circuits, which utilize either TDMA or FDMA access technologies. A modular CPE, expandable to accommodate future needs, is used to serve building sites with multiple small to medium tenants as well as larger, more bandwidth-intensive customers.

1.5.4.4 Alcatel Evolium

The Alcatel LMDS Solutions provides broadband last mile connections to thousands of subscribers from a single hub. It provides a wireless local infrastructure, using line-of-sight radio links over distances of up to 5 km, handling full two-way communications for more than 4000 end users, delivering true broadband capacity, at a bit rate of up to 8 Mbps through a wide variety of narrow- and broad-band communications services.

Alcatel LMDS utilizes co-polarized or cross-polarized, single carrier or multicarrier radio solutions to get the most out of the allocated spectrum. It supports a Guaranteed Cell Rate (capacity available at all times) and a Peak Cell Rate (maximum capacity available whenever there is spare capacity) on a per customer basis.

The air-interface makes use of a patented TDMA frame, which is optimized for any mix of circuit and packet data applications, with real time Dynamic Bandwidth Allocation. Among its advantages, there exist fibre-like reliability, 99.995 % availability, 10^{-14} BER, encryption over the air and on-line system upgrades with new features by in-band software download.

Alcatel LMDS operates in frequency bands between 10 and 43 GHz. Services include:

- circuit-switched voice, data or mixed voice/data;
- distributed or centralized architecture;
- multiservice cross-pole or mono carrier pole;
- virtual leased line (T1/E1 or $N \times 64$ Kbps);
- IP/Ethernet/ATM/Frame relay;
- bandwidth on demand.

The three components—Base Station, Customer Terminal Station and Network Management—constitute a star-architecture network which can be configured and reconfigured to meet the current and future access network requirements.

Base Station Each base station consists of a Radio Base Station (RBS) and a *Digital Base Station* (DBS) and serves as a hub for as many as 4,000 Network Terminations, transparently handling a virtually infinite variety of voice and high-rate data services. The base station is connected to the switching and routing platforms via any standard high-capacity transmission link.

Terminal Station Each Customer Terminal Station consists of a small (26 cm diameter) outdoor solid-state antenna (Radio Termination) and a simple interface unit (Network Termination). The terminal station is connected to a base station by a line-of-sight digital radio link.

Network and Service Management The Network Service Manager is a highly integrated open architecture solution for managing multitechnology, multiservice networks on a single platform. It extends the management reach of the operator from the wireline network in an integrated fashion into the broadband wireless access network.

1.5.5 Satellite-based Systems

These systems provide telephony services for rural communities and isolated areas such as islands. Satellite systems are designed for a Gaussian or Rician channel with K factor greater than 7 dB. These systems can be either of technology designed specifically for WLL applications or of technology piggybacked onto mobile satellite systems as an adjunct service [5]:

Of these, the former offers quality and grade of service comparable to wireline access, but it may be expensive. The latter promises to be less costly but, due to bandwidth restrictions, may not offer the quality and grade of service comparable to plain old telephone service (POTS). An example of a satellite-based technology specifically designed for WLL is the *Hughes Network Systems* (HNS) *telephony earth station* (TES) technology. This technology can make use of virtually any *geostationary earth orbit* (GEO) C-band or Ku-band satellite. Satellite technology has been used to provide telephony to remote areas of the world for many years. Such systems provide an alternative to terrestrial telephony systems where landlines are not cost-effective or where an emergency backup is required. There are several proposed systems for mobile satellite service, including the *Inmarsat International Circular Orbit* (ICO) system, Globalstar, and *American Mobile Satellite Corporation* (AMSC) system. These systems are specialized to support low-cost mobile terminals primarily for low bit rate voice and data applications. Fixed applications are a possible secondary use to mobile applications. There is a great deal of difference between these systems, especially when considering the orbit and the resultant propagation delay. The number of satellites and the propagation delay pose very different constraints on system design, so that there is no true representative system. For example, GEO satellite systems are not required to support handover even for most mobile applications. *Mid-earth orbit* (MEO) and *low earth orbit* (LEO) satellite systems require handover capability for all fixed and mobile applications because the satellites are in motion relative to the earth's surface even when the terrestrial terminal is fixed. This can be problematic if the handover is supported in the switch because *mobile switching centres* (MSCs) support sophisticated mobility functions such as link handover, but do not typically support ordinary switching functions such as hunt groups, for example, which are highly desirable in a WLL system.

1.5.5.1 HNS Terminal Earth Station Quantum System

The HNS terminal earth station (TES) product is used for the Intelsat network to provide remote-access telephone service [33]. It is one of those systems utilizing geostationary satellites and can offer wireless local access in areas where copper cable is difficult or even much expensive to use. The TES system is a satellite-based telephony and data communications network providing mesh connectivity between multiple earth stations. The system provides call-by-call *demand-assigned multiple access* (DAMA) circuits and pre-assigned circuits, via single hop *single channel per carrier* (SCPC) communications paths between earth stations. It supports both public and private networks, and is capable of operating with any telephony interface from individual subscribers to toll switches and major gateways.

An outdoor RF terminal and antenna plus indoor IF and baseband equipment perform the wireless access subscriber unit functions. *High-power amplifier* (HPA) power options include 5, 10, and 20 W for C-band and 2, 5, 8, and 16 W for Ku-band. A small reflector antenna of 1.8–3.8 m diameters is required. TES remote terminals communicate with each other and the *network control system* (NCS) using virtually any Ku- or C-band satellite, using single channel per carrier access to the satellite.

The air-interface employs quadrature phase shift keying (QPSK) or *binary phase shift keying* (BPSK) modulation, depending upon the user information and coding rates. FEC is provided at rate 1/2 or rate 3/4. Scrambling is used to spread the transmitted energy across the satellite channel bandwidth. Differential coding resolves phase ambiguity in the demodulated signals. Voice is coded using 32 kbps adaptive differential pulse code modulation (ADPCM) (ITU-T G.721) or 16 kbps low delay-code excited linear predictive (LD-CELP) (ITU-T G.728).

The terrestrial interfaces toward the user which are supported by TES include four- and two-wire *ear and mouth* (EM) or *single-frequency* (SF) inband signalling, RS-232, RS-449, and V.35 data interfaces. In addition, single-line versions supporting two-wire, RS-232, and ISDN interfaces are provided whereas multiline access to a PBX can also be supported. The TES ISDN earth station provides 56 kbps pulse coded modulated (PCM) voice. The wireless access network unit equipment logically includes the satellite, terminal equipment, and the Network Control System. Voice calls and asynchronous data calls can be made on demand under the control of the centralized DAMA processing equipment of the NCS. Satellite channels for user information are allocated only for the duration of these connections.

TES supports telephony, synchronous and asynchronous data, facsimile, ISDN BRI data, and E1 and T1 trunking between remote terminals anywhere in the system. Voice and data traffic is transferred directly between remote terminals, not via the NCS, to minimize the delay using a single satellite hop. Features and services are based on the remote PBX rather than on the centralized PSTN interface, which is an E1 or T1 trunk.

1.6 Comparison of WLL Services

Wireless local loop as an access network technology competing with its wire-line counterparts, has to support the full range of Telecommunication Services: Telephony, Fax, Voice-band Data Modems, Leased Line Data and Basic Rate ISDN. It has to be fully compatible with the public network and fully transparent with other access equipment. It must ensure an inherently secure radio interface and simple Installation, Operation and Maintenance procedures. Apart from circuit-switching services, WLL must be capable of offering packet-switching data services such as X.25, X.21, Frame Relay and IP as well. Particularly, the broadband systems must support broadband standards like ATM and SDH to connect transparently to the installed wireline network infrastructure, Figure 1.4.

Table 1.3 gives a summary of the WLL technologies mentioned in the previous sections. As shown in the table, all systems with the exceptions of 900 MHz cellular ones offer toll quality voice services and medium to high-rate data services. Among these systems, cordless and proprietary broadband wireless access, are characterized by short-range radio technology and very high-rate data services. Especially, the broadband wireless access systems are of equal capacity to their broadband wireline counterparts, fibre, coaxial cable and ADSL. These characteristics make such systems as the most appropriate WLL choice for developed regions and/or especially urban/suburban areas.

On the other hand, cellular and satellite WLL systems are characterized by high-range radio technology but low to medium-quality voice and low to medium-rate data services.

Table 1.3 Summary of WLL services

	Cordless	Cellular		Proprietary Narrowband (FWA)	Proprietary Broadband (BWA)	Satellite-Based Systems
		2nd Generation	3rd Generation			
	DECT/ PACS/ PHS	GSM/IS-95	W-CDMA	Proximity/ Airspan/ Multigain	Allreach/ Spectrapoint/ Reunion/ Evolium	HNS Quantum System
Voice Codec	32 Kbps ADPCM 64 Kbps PCM	13 Kbps RPE-LTP/ 13 Kbps CELP	64 Kbps PCM 32 Kbps ADPCM 16 Kbps LD-CELP	64 Kbps PCM 32 Kbps ADPCM	32 Kbps ADPCM	32 Kbps ADPCM 64 Kbps PCM
Data rate up to/ Service capability	504 Kbps/ 256 Kbps BRA ISDN	9.6 Kbps 182.4 Kbps (GPRS)*/ 115.2 Kbps (IS-95B)*	114 Kbps BRA ISDN	128 Kbps BRA ISDN	45 Mbps (Downlink)/ 10 Mbps (Uplink) PRA ISDN	144 Kbps BRA ISDN
Range/ cell size	Low/small	High/large	High/large	Medium	Low/small	Very High/very large
Quality	Excellent	Medium	Medium	Excellent	Excellent	Medium
Frequencies	Standard	Standard	Standard	Standard	Standard	Custom

* Only with channel aggregation techniques.

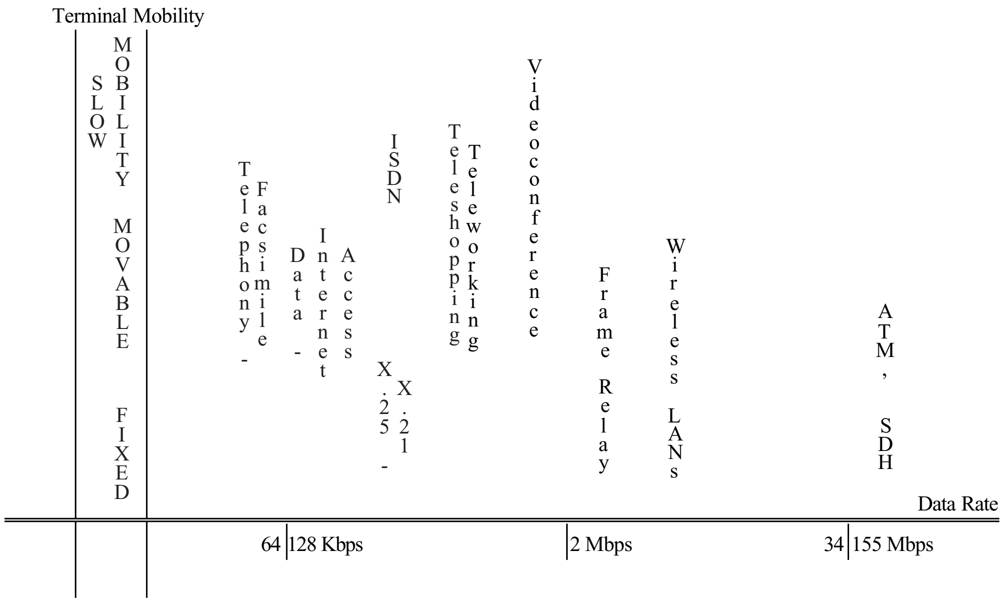

Figure 1.4 WLL applications supported at various terminal speeds and data rates

Hence, they are the appropriate choice for developing regions and/or rural areas and villages. Last, medium-rate data services and toll-quality voice characterize proprietary narrowband WLL systems. Their range can be as high as 40 km, which makes them ideal for deployments without capacity limitations. Finally, only the proprietary broadband systems, known also as LMDS or Point-to-Multipoint (PMP), offer local loop access for future multimedia applications such as video distribution.

Appendix A Fixed versus Mobile Cellular Systems

WLL is only a fixed wireless communication system using implemented wireless technologies to compete its wireline counterparts. It has the philosophy of fixed communication systems regarding terminal mobility at both ends of the transmission link such as terrestrial microwave point-to-multipoint and satellite microwave systems. Hence, due to the nature of the wireless communication medium, there are certain advantages to implementing a WLL rather than a mobile system. These advantages emanate from the following reasons:

- A WLL has a fixed-to-fixed propagation path. The path loss of the fixed-to-fixed propagation in a WLL was based on 20 dB/decade (propagation path-slope, $g = 2$) in [34]. The path loss of the fixed-to-mobile propagation (i.e. cellular system) is often based on 40 dB/decade ($g = 4$). The path loss exponent is not dependent on the speed of either end of the link. Typically, the path loss exponent g lies between 3 and 5.
- In a WLL, the antennas are usually located at high spots. This implies that in a WLL system the received signal experiences less fading than in the fixed-to-mobile condition. The design E_b/N_0 ratio under the fixed-to-fixed condition for a 30 kHz channel is

assumed to be 14 dB, whereas the design E_b/N_0 ratio under a mobile radio condition for a 30 kHz channel is 18 dB.

- In a WLL, the frequency re-use distance can be reduced because in a WLL the fixed-to-fixed link may use directional antennas on both ends, so the interference area becomes small. A reduction in frequency re-use distance may provide an increase in the capacity.
- In a WLL, the use of adaptive antenna arrays on both the base and user stations does also increase the capacity making efficient use of spectrum [35].
- In a WLL, no handoffs occur because it is a fixed-to-fixed link. Also, the air link from each building to the cell site can be customarily installed to reduce the interference. Since the link remains unchanged (provided there is not too much growth and/or cell splitting) after installation, the design of the WLL system is much simpler than that of a mobile system.
- Since the WLL signal channel is a Gaussian noise channel or strong Rician channel (not a Rayleigh fading channel); no interleaving of the data stream is needed. Thus, data compression schemes and quadrature amplitude modulation (QAM) can be applied efficiently to generate a high rate throughout, although the radio transmission rate is as low as 14.4 kbps.

Appendix B CDMA versus TDMA in WLL

Reviewing W. Webb's book [29], which constitutes an introduction to WLL, it is easily concluded that the first WLL systems were narrowband cellular systems properly adapted to the fixed subscriber conditions. CDMA and TDMA were the only multiple access techniques supporting the various air-interfaces. For this reason, the author has tried a detailed comparison of these two techniques in several aspects in order to distinguish the most efficient. It is interesting to see these aspects one by one.

1. Range It is claimed that CDMA systems have a greater range than equivalent TDMA systems. Range is related to the path loss and the minimum signal level that the receiver can decode reliably. Path loss is independent of multiple-access methods, so the claim is basically one that CDMA can work with lower received signal strength than TDMA. This is true, since the receiver applies a gain, G, to the received signal with a CDMA network but not with a TDMA network. However, to counteract that, TDMA systems need only operate at a higher power level. Such an option is not possible with cellular systems because high power levels rapidly drain mobile batteries; power, however, is rarely a concern for a WLL operator. There seems little reason to support the claim that CDMA systems must have a greater range than TDMA systems.

2. Sectorization Sectorization is the division of a circular cell into a number of wedge-shaped sectors. It is claimed that if sectorization is performed in a CDMA network, the number of sectors deployed can use the same frequency in each sector, increasing the capacity of the system. That claim is correct. It also is claimed that using sectors in a TDMA arrangement does not increase capacity. That also is broadly correct. Fundamentally, when a cell is sectorized, the cell radius remains the same. Hence, the transmitted power remains the same, and the distance, that is required to the next cell using the same frequency also remains the same. However, because there are now more cells within the sterilization radius, more frequencies, need to be found to avoid interference. So although the sector is smaller than the cell and thus has to support less traffic, it also has fewer frequencies on which to do that (because the total frequency assignment has been divided by a larger cluster size). That is not the case with CDMA, where using the same frequency in adjacent sectors increases only slightly the interference to neighbouring cells and slightly reduces their capacity.

TDMA could achieve a real gain if, instead of dividing a cell into a number of smaller cells by sectorization, the cell was divided into smaller circular cells, that is, the base stations were distributed around the cell and transmitted on a lower power level. That approach results in similar equipment costs but much higher site rental and backhaul costs; thus, it tends to be avoided except where absolutely necessary. In summary, the CDMA capacity can he increased by a factor of 2 to 3 by sectorization with only a small increase in cost. The option is not available in TDMA and hence represents an advantage of CDMA.

3. Frequency Planning When different frequencies need to be assigned to neighbouring cells, the network planners have to decide which frequencies to use in which cells. In a CDMA system, where each frequency is used in each cell, no such decision needs to be made. For that reason, it is true that, in general, CDMA does not require frequency planning, although it may require PN code assignment planning. However, that is not a major advantage. Frequency planning can be readily accomplished with today's planning tools and easily adjusted if problems occur. DCA systems do not require frequency planning in any case. Finally, some CDMA WLL systems suggest that frequency planning be performed on a cluster size of 2, for various design reasons, so some frequency planning is required. In summary, frequency planning is not a key issue in the selection process for CDMA.

4. Operation in Unlicensed Bands A number of frequency bands are unlicensed, that is, anyone can use them without having to obtain a license from the regulator. Such bands typically are used by *industrial, scientific, and medical* (ISM) applications, for example, ovens that use radio for heating purposes. Operating WLL systems in those bands has the single attraction that the spectrum is free and that the need to apply for a license is removed. However, the WLL system will suffer unknown and variable interference from uncontrolled sources.

These bands can be used only if the system can tolerate the interference. CDMA implicitly tolerates interference anyway, so in such an environment a CDMA system will work, but with reduced capacity. 'I'DMA systems cannot accommodate such interference, implicitly, but there are techniques that allow them to do so. DCA selects channels according to the interference present on them. Another technique, frequency hopping, moves rapidly from channel to channel, so interference on one channel causes errors only for a short period of time.

CDMA systems cope slightly well with interference because they still use interfered channels but at a lower capacity, whereas TDMA systems use techniques to avoid transmitting on the channels. The capacity of a CDMA system probably is higher, then, in such an environment.

5. Macrocells versus Microcells By using small cells in high-density areas, there are situations where smaller WLL cells are deployed within the coverage area of larger WLL cells. That is a problem for CDMA systems. Subscriber units configured for the larger cell will operate with much higher powers than those configured for the smaller cells. If both cells operated on the same frequency, the capacity of the smaller cell would be near zero, so different frequencies must be used. Because of the wide bandwidth and hence high-capacity of a CDMA system, that may be inefficient, in the worst case reducing the equivalent CDMA capacity by a factor of 2. Such reduction does not occur in TDMA, because the cells would be assigned different frequencies in any case.

The actual effect of microcells will vary from network to network, but with good planning, capacity reductions of far less than 2 should be realisable.

6. Risk TDMA systems have been widely deployed around the globe, while CDMA systems are far behind in number of built-up systems. There is a much higher risk with CDMA that equipment will be delayed, will not provide the promised capacity, will prove difficult to frequency plan, and so on. Such risks are continually reducing as experience with CDMA systems grows rapidly. Till now, however, the risk seems to have disappeared almost completely and the technology has matured very much among the manufacturers. Operators around the globe have started to take on such risks by establishing networks based on the CDMA air-interface as this has progressed all these years.

7. Cost Everything eventually comes down to cost. At the moment, CDMA system components cost more than TDMA system components. However, because of the higher capacity of CDMA systems, fewer base stations are required, resulting in lower equipment bills and lower site and line-rental costs. How the two facts balance depends on the actual difference in equipment costs and the extent to which the network is capacity limited. Certainly, in a highly capacity-limited situation, CDMA systems should prove less expensive.

8. Bandwidth Flexibility CDMA systems can increase the user bandwidth simply by reducing the gain factor G. TDMA systems also can be bandwidth flexible by assigning more than one TDMA slot per frame to a user. For example, DECT systems can assign between 32 and 552 Kbps dynamically to one user, depending on the load. Thus, both access methods are inherently, equally flexible although manufacturers may not have designed the capability into individual systems.

References

[1] V. K. Garg and E. L. Sneed, 'Digital Wireless Local Loop System,' *IEEE Commun. Mag*., vol. 34, no. 10, pp. 112–115, Oct. 1996.

[1] B. Khasnabish, 'Broadband to the Home (BTTH): Architectures, Access Methods, and the Appetite for it,' *IEEE Network*, vol. 11, no. 1, pp. 58–69, Jan./Feb. 1997.

[2] H. Huh, S. C. Han and D. G. Jeong, 'WLL Services using Cellular Mobile Network,' Shinsegi Telecomm R&D/TR P2-97-04-02, Apr. 1997.

[3] H. Salgado, 'Spectrum Allocation for Fixed Wireless Access Technologies in the Americas,' in *Proc. IEEE VTC '98*, Ottawa, Canada, pp. 282–187, May 1998.

[4] A. R. Noerpel and Y. -B. Lin, 'Wireless Local Loop: Architecture, Technologies and Services,' *IEEE Personal Commun*., vol. 5, no. 3, pp. 74–80, June 1998.

[5] W. C. Y. Lee, 'Spectrum and Technology of a Wireless Local Loop System,' *IEEE Personal Commun*., vol. 5, no. 1, pp. 49–54, Feb. 1998.

[6] C. R. Baugh, E. Laborde, V. Pandey and V. Varma, 'Personal Access Communications System: Fixed Wireless Local Loop and Mobile Configuration and Services,' *Proc. IEEE*, vol. 86, no. 7, pp. 1498–1506, July 1998.

[7] C. C. Yu, D. Morton, C. Stumpf, R. G. White, J. E. Wilkes and M. Ulema, 'Low-Tier Wireless Local Loop Radio Systems, Part 1: Introduction,' *IEEE Commun. Mag*., Mar. 1997.

[8] C. C. Yu, D. Morton, C. Stumpf, R. G. White, J. E. Wilkes and M. Ulema, 'Low-Tier Wireless Local Loop Radio Systems, Part 2: Comparison of Systems,' *IEEE Commun. Mag*., Mar. 1997.
[9] Z. I. Kostic and S. Seetharaman, 'Digital Signal Processors in Cellular Radio Communications,' *IEEE Commun. Mag*., Dec. 1997.
[10] M. P. Lotter and P. van Rooyen, 'CDMA and DECT: Alternative Wireless Local Loop Technologies for Developing Countries,' in *Proc. IEEE PIMRC '97*, Helsinki, Finland, pp. 169–173, Sep. 1997.
[11] TIA/EIA/IS-95-A, Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System, 1995.
[12] ANSI J-STD-008, Personal Station-Base Station Compatibility Requirements for 1.8 to 2.0 GHz Code Division Multiple Access (CDMA) Personal Communications Systems, 1996.
[13] TIA/EIA/SP-3693 (to be published as TIA/EIA-95), Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System, Baseline Version, July 1997.
[14] D. N. Knisely, S. Kumar, S. Laha and S. Nanda, 'Evolution of Wireless Data Services: IS-95 to cdma2000,' *IEEE Commun. Mag*., vol. 36, no. 10, pp. 140–149, Oct. 1998.
[15] D. G. Jeong and W. S. Jeon 'CDMA/TDD System for Wireless Multimedia Services with Traffic Unbalance between Uplink and Downlink,' *IEEE J. Select. Areas Commun*., vol. 17, no. 5, pp. 939–946, May 1999.
[16] ETSI/SMG/SMG2, The ETSI UMTS Terrestrial Radio Access (UTRA) ITU-R RTT Candidate Submission, Jan. 1998.
[17] Ad-hoc T, IMT-2000 Study Committee of ARIB, Japan's Proposal for Candidate Radio Transmission Technology on IMT-2000: W-CDMA, June 1998.
[18] TIA TR-45.5, The cdma2000 ITU-R RTT candidate submission, June 1998.
[19] TR41.6/96-03-007, Personal Wireless Telecommunications—Enhanced (PWT-E) Interoperability Standard (PWT-E), July 1996.
[20] ETS 300 175, Digital Enhanced Cordless Telecommunications (DECT); Common Interface (CI), European Telecommunications Standards Institute (ETSI), 1992.
[21] D. Akerberg, F. Brouwer, P. H. G. van de Berg and J. Jager, 'DECT Technology for Radio in the Local Loop,' in *Proc. IEEE VTC '94*, Stockholm, Sweden, pp. 1069–1073, June 1994.
[22] M. Gagnaire, 'An Overview of Broad-band Access Technologies,' *Proc. IEEE*, vol. 85, no. 12, pp. 1958–1972, Dec. 1997.
[23] M. Zanichelli, 'Cordless in the Local Loop,' in *Cordless Telecommunications in Europe*, W. Tuttlebee, Ed., Springer-Verlag, London, 1997.
[24] ANSI J-STD-014, Personal Access Communications Systems Air Interface Standard, 1995.
[25] A. R. Noerpel, Y. B. Lin and H. Sherry, 'PACS: Personal Access Communications System—A Tutorial,' *IEEE Personal. Commun*., pp. 32–43, June 1996.
[26] A. R. Noerpel, 'WLL: Wireless Local Loop—Alternative Technologies,' in *Proc. IEEE PIMRC*, Helsinki, Finland, 1997.
[27] R. C. Schulz, 'Wireless Technology and PCS Applications,' *GLA Int'l*, 1996.
[28] W. Webb, *Introduction to Wireless Local Loop*, Artech House, London, 1998.
[29] G. M. Stamatelos and D. D. Falconer, 'Milimeter Radio Access to Multimedia Services via LMDS,' in *Proc. IEEE GLOBECOM '96*, London, UK, pp. 1603–1607, Nov. 1996.
[30] W. Honcharenko, J. P. Kruys, D. Y. Lee and N. J. Shah 'Broadband Wireless Access,' *IEEE Commun. Mag*., Jan. 1997.
[31] J. Zhuang and M. E. Rollins, 'Forward Link Capacity for Integrated Voice/Data Traffic in CDMA Wireless Local Loops,' in *Proc. IEEE VTC '98*, Ottawa, Canada, pp. 1578–1582, May 1998.
[32] 'TES Quantum,' Tech. Rep. 1022896-0001, rev. B, Hughes Network Systems, 1996.
[33] W. C. Y. Lee, 'Applying CDMA to the Wireless Local Loop,' *Cellular Business*, pp. 78–86, Oct. 1995.
[34] A. G. Burr, 'A Spatial Channel Model to Evaluate the Influence of Directional Antennas in Broadband Radio System,' *IEE Colloquium on Broadband Digital Radio*, 1998.